Large & Small Blades: Design & Manufacturing

Tailored Twist-Flap Coupling

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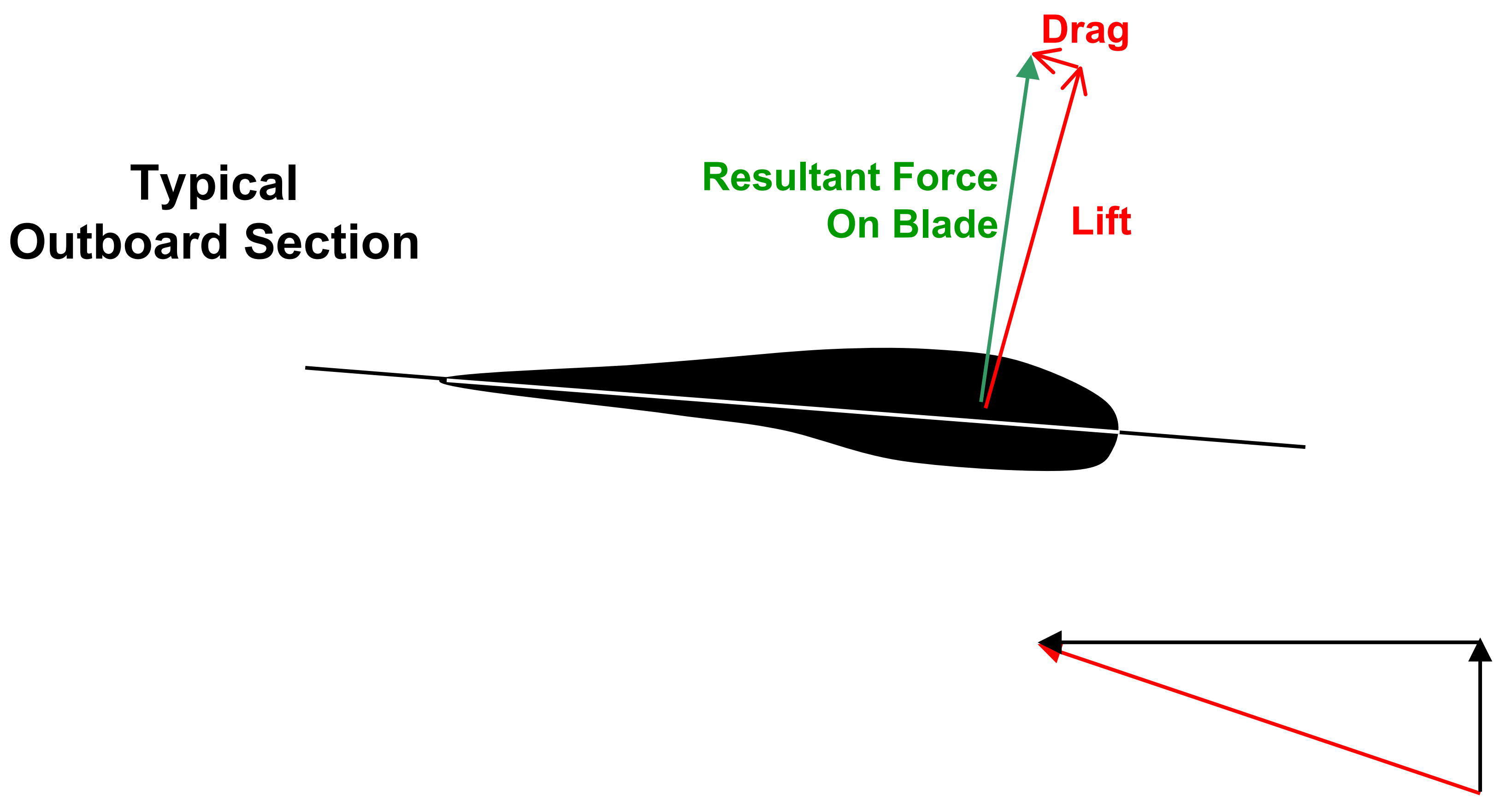
Tailored Twist-Flap Coupling

- Tailored twist-flap coupling can be used to shed transient loads, thereby reducing fatigue
- Allow an increase in rotor diameter
- Increased Energy Capture
- Value of increased energy capture exceeds cost of implementing coupling
- Reduction in the cost of energy

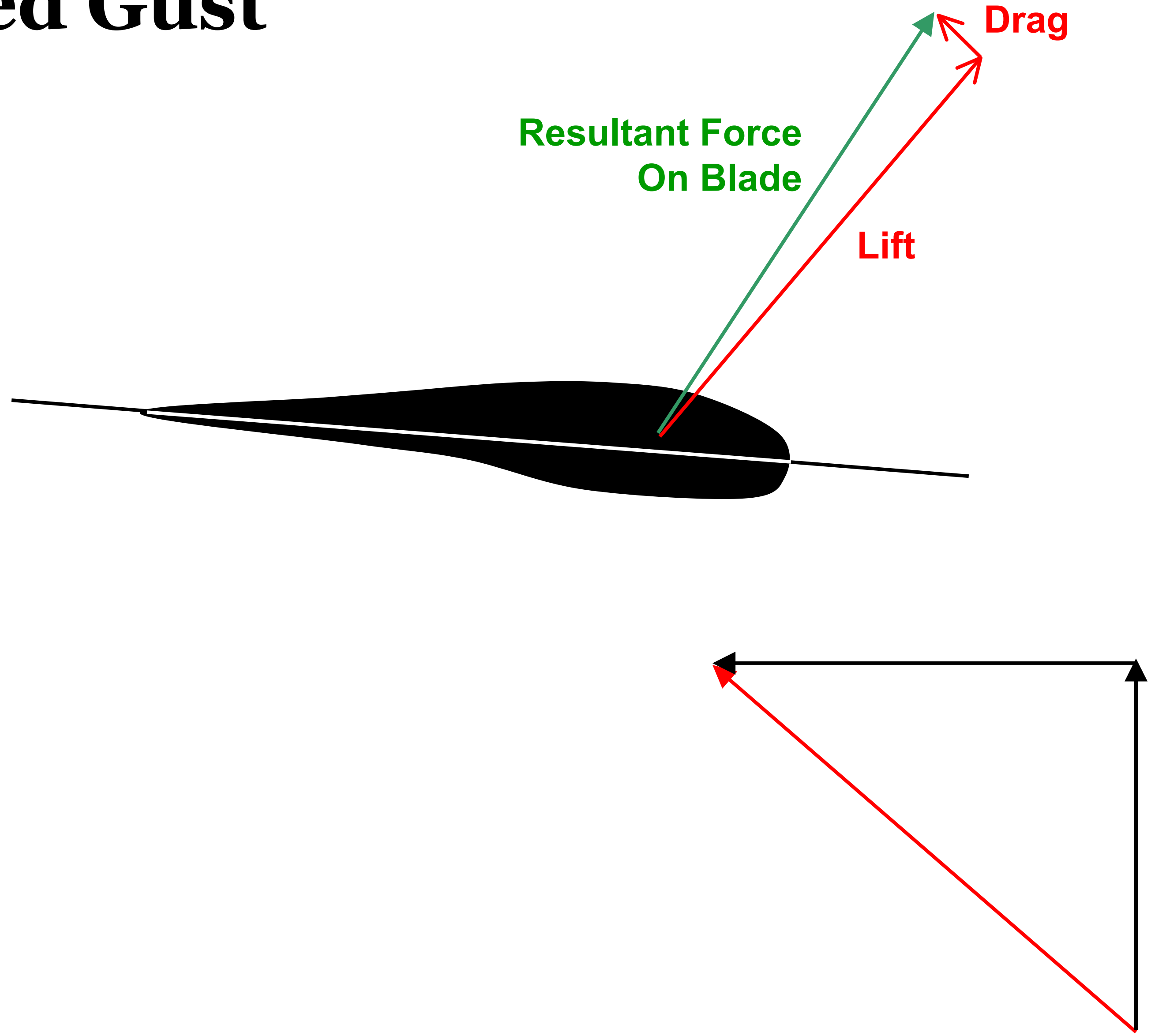
Wetzel Engineering
Twist-Flap Coupled Blade Studies

- 3-m Blades for a 6-kW Turbine
  - USDOE Distributed Wind Generation Contract
- 9-m Blades for Sandia's 115-kW LIST Turbine
  - Subcontractor to Wichita State University
- 34/37/39-m Blades for GE Wind's 1.5-MW Turbine
  - USDOE STTR Contract
  - Subcontractor to GE Wind (NGT Program)

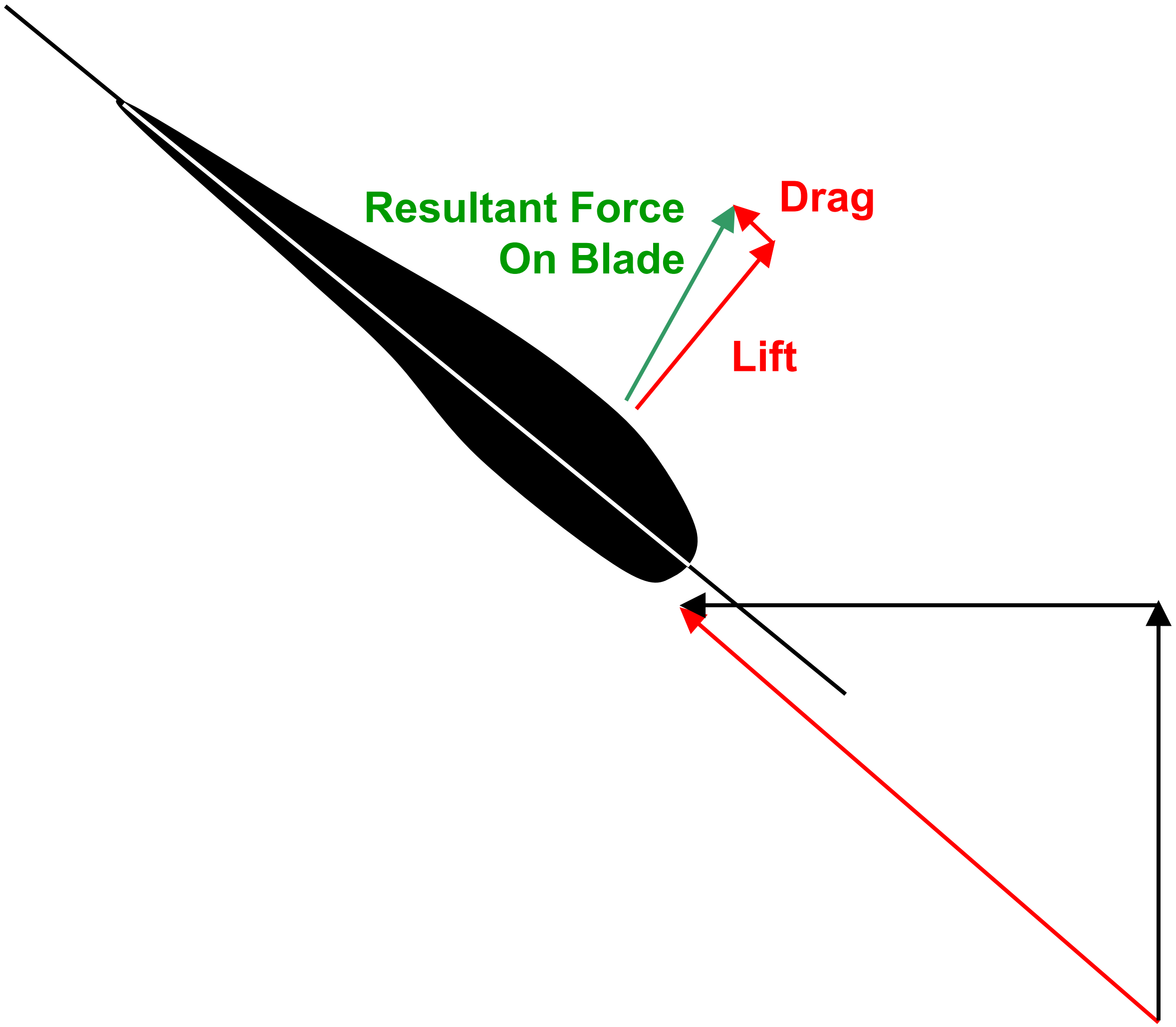
Normal Operation



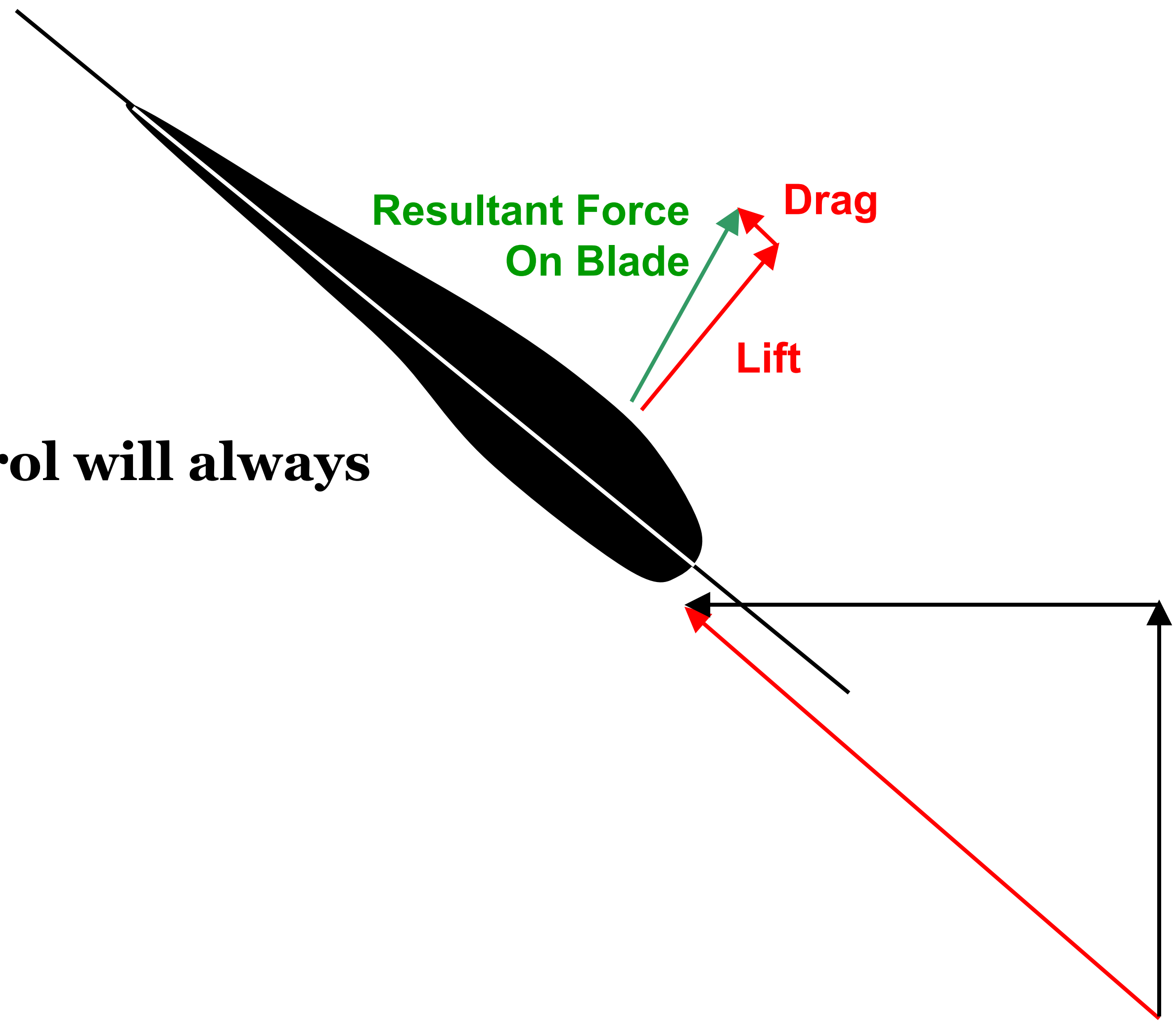
High-Speed Gust



High-Speed Gust: Pitch Regulation

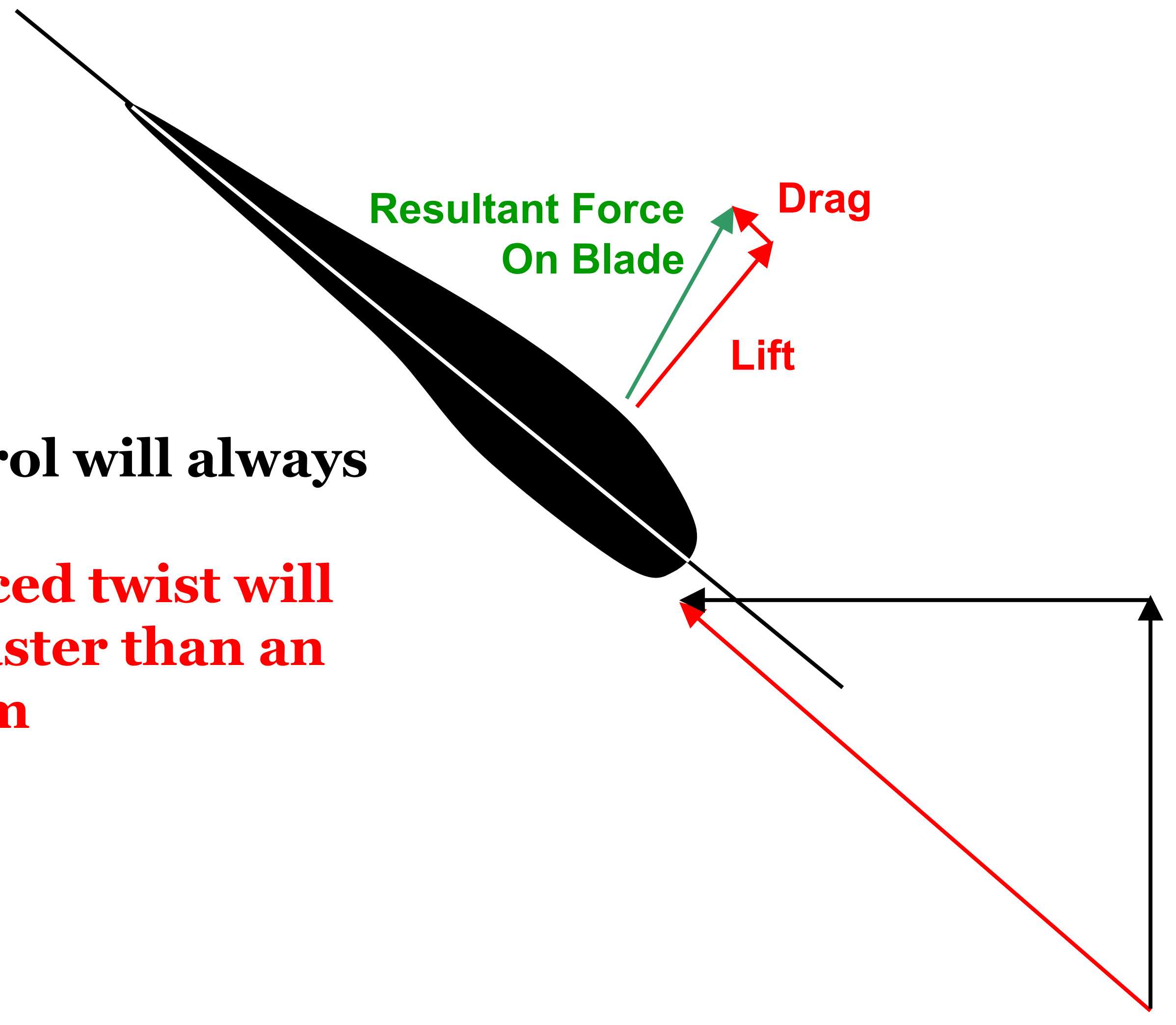


High-Speed Gust: Pitch Regulation



- **Active Pitch Control will always experience lag**

High-Speed Gust: Twist-Flap Coupling



- Active Pitch Control will always experience lag
- Passive flap-induced twist will always respond faster than an active pitch system

Comment on the Governing Equations

The Common Formulation of Twist-Flap Coupling Used in Recent Years is Incorrect

$$\begin{Bmatrix} M_x \\ T \end{Bmatrix} = \begin{bmatrix} EI & -g \\ -g & GJ \end{bmatrix} \begin{Bmatrix} \kappa_x \\ \phi_x \end{Bmatrix}$$

Inverted, this yields

$$\begin{Bmatrix} \kappa_x \\ \phi_x \end{Bmatrix} = \frac{1}{1-\alpha^2} \begin{bmatrix} \dfrac{1}{EI} & \dfrac{\alpha^2}{g} \\ \dfrac{\alpha^2}{g} & \dfrac{1}{GJ} \end{bmatrix} \begin{Bmatrix} M_x \\ T \end{Bmatrix}$$

where $\alpha = \dfrac{g}{\sqrt{EI \cdot GJ}}$

When T=0, then $\kappa_x = \dfrac{M_x}{EI\left(1-\alpha^2\right)}$ **which is incorrect!**

It can be shown that the classic, well known relationship

$$\kappa_x = \frac{M_x}{EI}$$

is always true, even when coupling is present

Comment on the Governing Equations

Correct Formulation

$$\begin{Bmatrix} \kappa_x \\ \phi_x \end{Bmatrix} = \begin{bmatrix} \dfrac{1}{EI} & \dfrac{\alpha^2}{g} \\ \dfrac{\alpha^2}{g} & \dfrac{1}{GJ} \end{bmatrix} \begin{Bmatrix} M_x \\ T \end{Bmatrix}$$

Inverted, this yields

$$\begin{Bmatrix} M_x \\ T \end{Bmatrix} = \frac{1}{1-\alpha^2} \begin{bmatrix} EI & g \\ g & GJ \end{bmatrix} \begin{Bmatrix} \kappa_x \\ \phi_x \end{Bmatrix}$$

When T=0, then $\kappa_x = \dfrac{M_x}{EI}$ **which is Correct!**

Previous Conclusions that Twist-Flap Coupling Introduces an Inherent flapwise softening due to the 1-α^2 term are incorrect. No such softening occurs.

Rotating axial fibers will obviously reduce the axial stiffness, but no additional softening occurs due to coupling.

Comment on the Governing Equations

We could use a formulation which avoids the use of EI, GJ, or g

$$\begin{Bmatrix} M_x \\ T \end{Bmatrix} = \begin{bmatrix} K_{11} & K_{21} \\ K_{12} & K_{22} \end{bmatrix} \begin{Bmatrix} \kappa_x \\ \phi_x \end{Bmatrix}$$

This is essentially what we do when we build the stiffness matrix in ADAMS from ANSYS results

We calculate the K terms from ANSYS and plug them into ADAMS

The error is in how we relate the K terms to EI, GJ, & g

Comment on the Governing Equations

If you use the incorrect formulation consistently between models (e.g., ANSYS & ADAMS), you will obtain consistent and correct answers in terms of deflections, dynamics, etc.
That is, Two Wrongs Seem to Make it Right!

Incorrectly putting the $1-\alpha^2$ term in the Denominator of the Flexibility Matrix Results in an Overestimation of EI by the factor of approximately α^2. However, putting the $1-\alpha^2$ term in the denominator overestimates the flexure resulting from a given EI by the same factor!

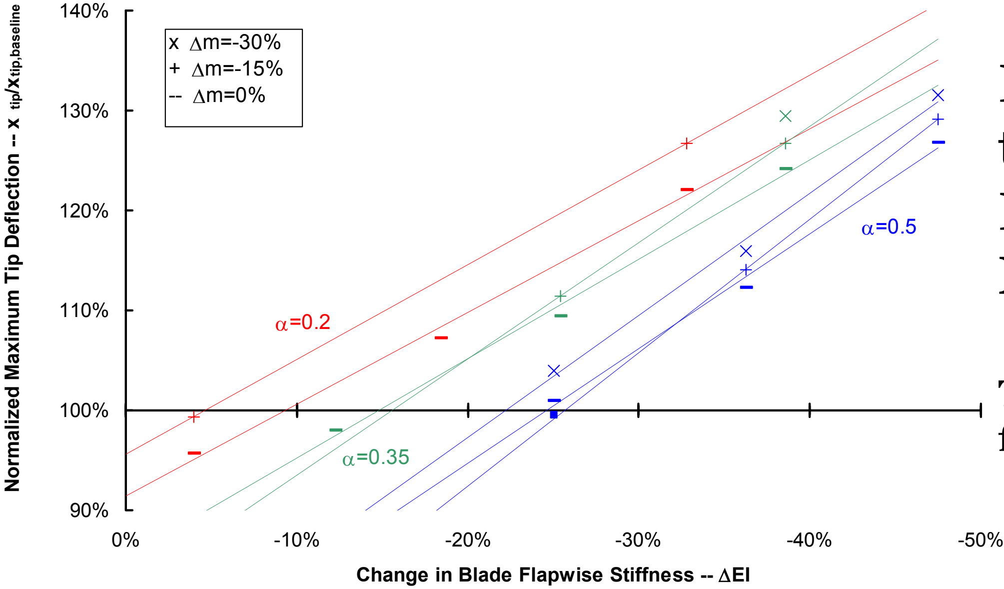
Comment on the Governing Equations

However, if you calculate E and I from a cross-sectional equivalent beam property model, you must use the correct formulation of the governing equations in order to get the correct answer

Similarly, if you hand EI data calculated using the incorrect formulation to someone using the classic, correct definition of EI, they will obtain a different, inconsistent, and incorrect answer.

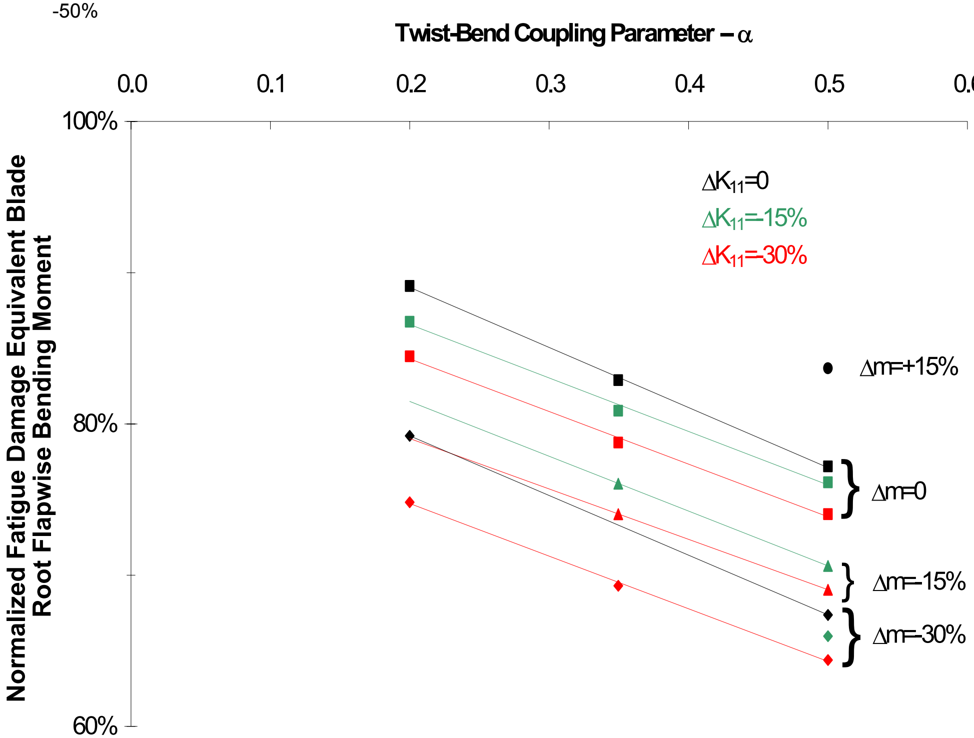
This problem needs to be corrected.

Influence of Coupling on Dynamics



Results of Parametric Studies of the Dynamics of 37-m Twist-Flap Coupled Blades on a 1.5-MW Pitch-Regulated Turbine

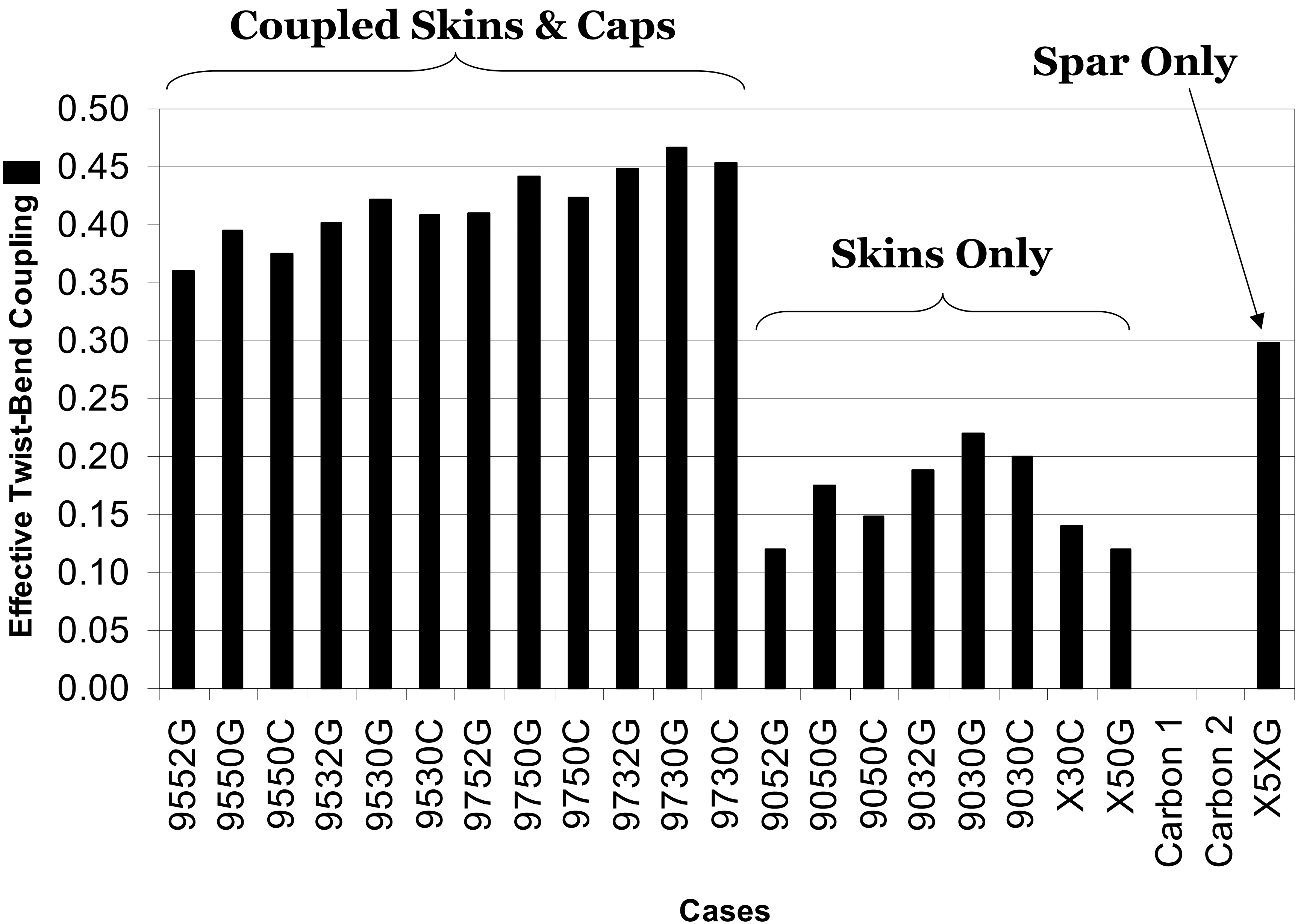
Thanks to GE Wind & Windward Engineering for their Support



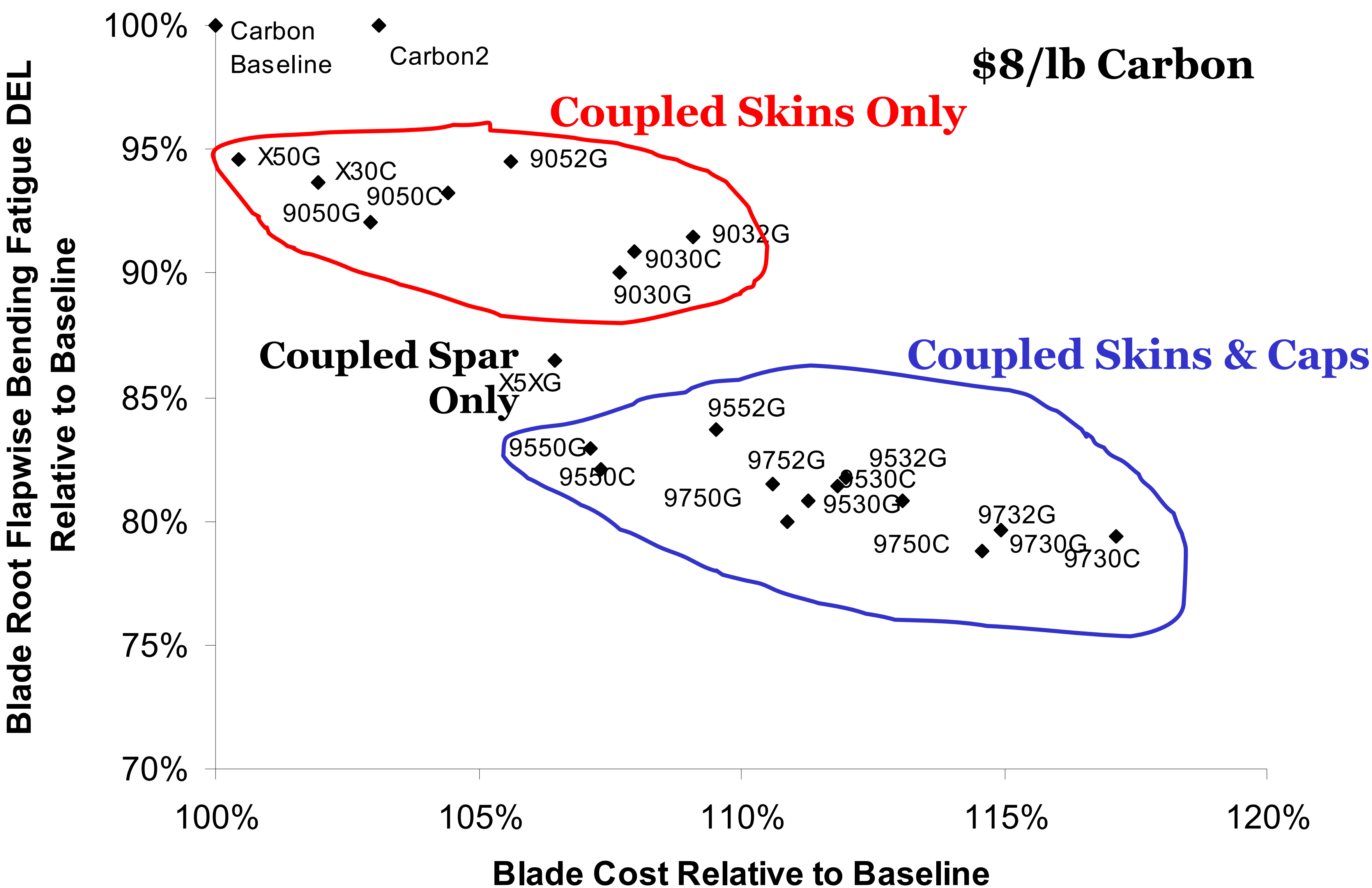
Load Trimming due to Coupling actually permits flapwise softening of the blade without an increase in tip deflection.

Substantial Reductions in Flapwise Fatigue can be Achieved with Coupling

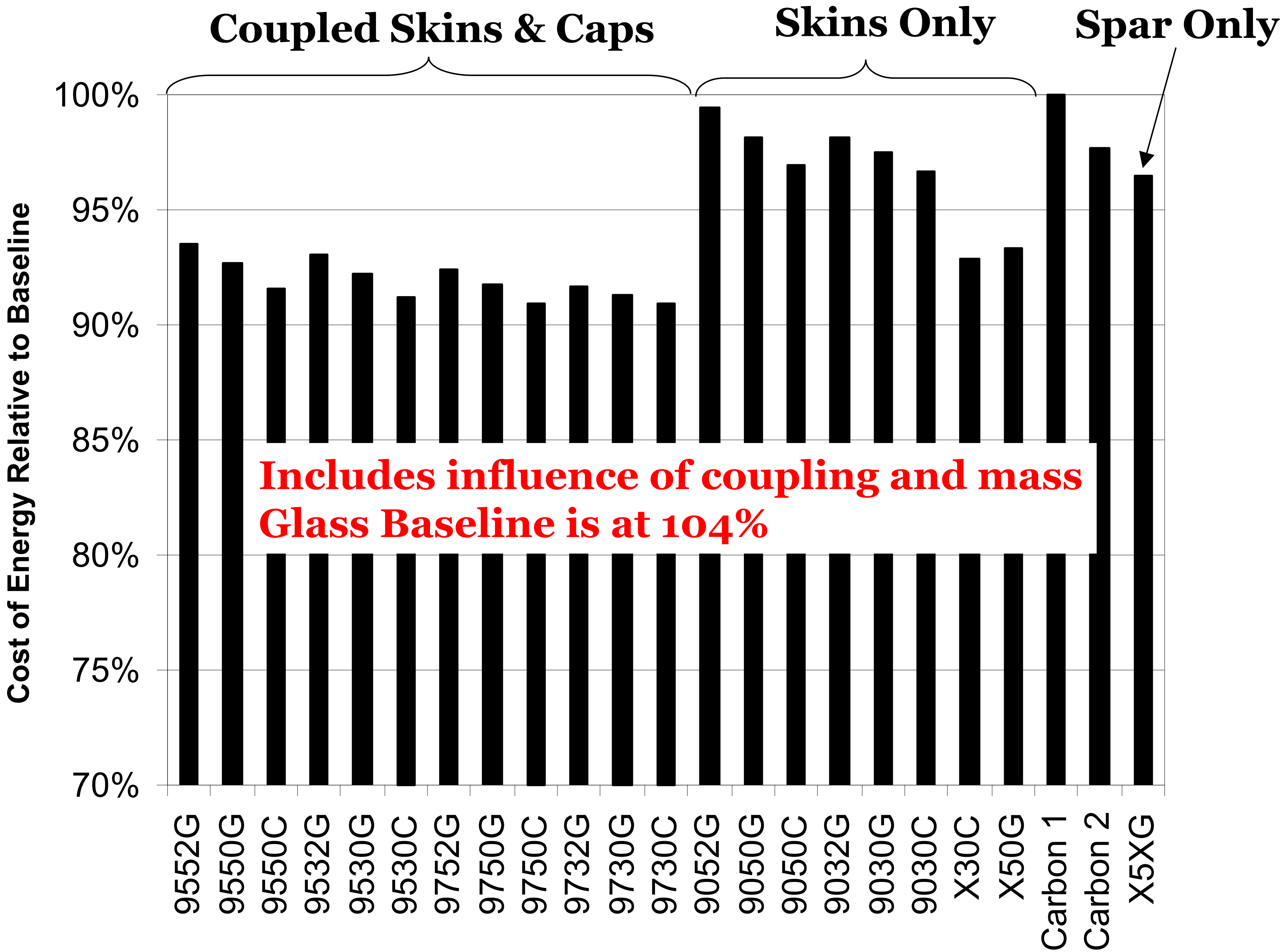
37-m Blade Structural Design Studies



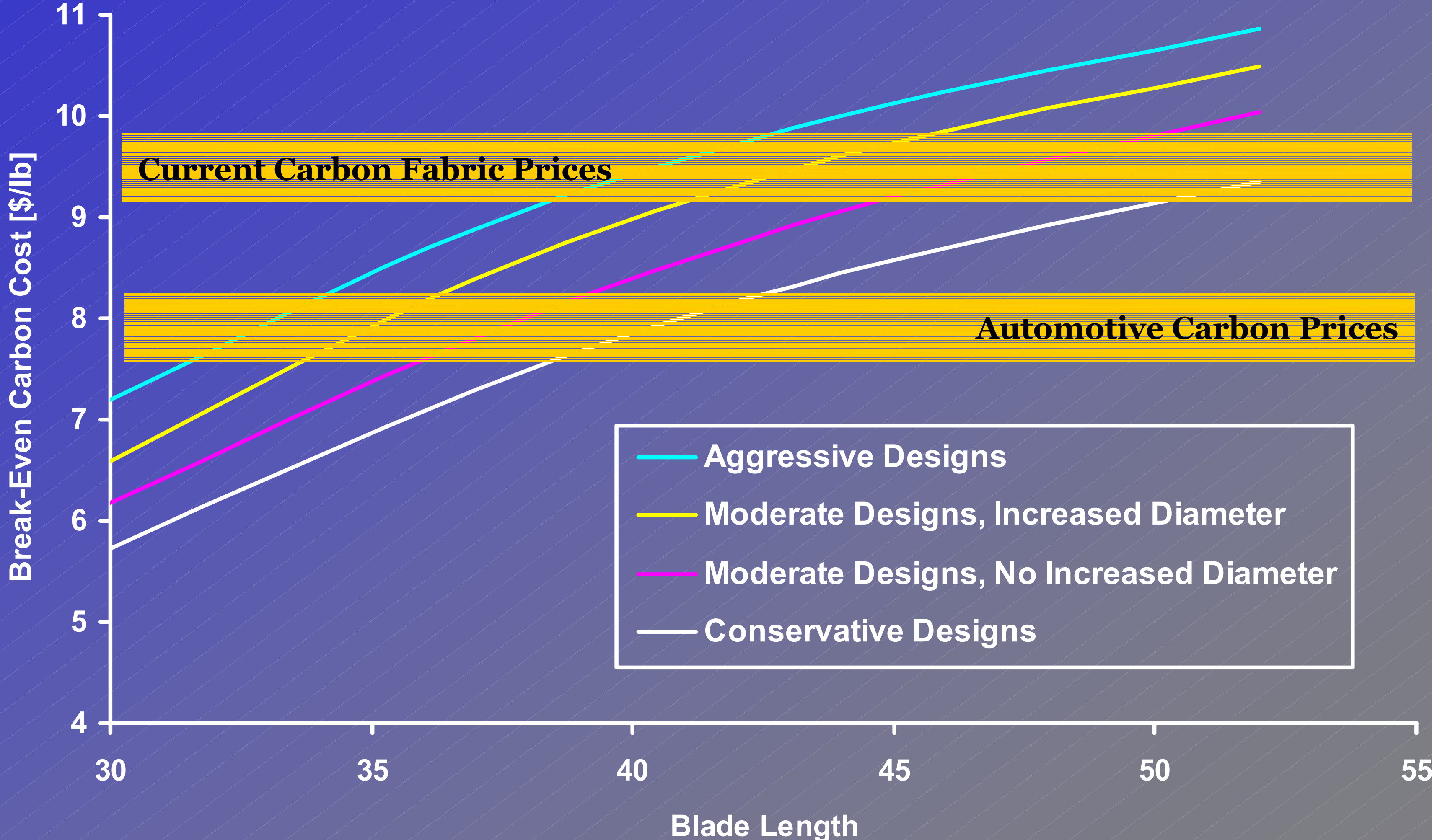
Influence of Coupling on Cost & Fatigue



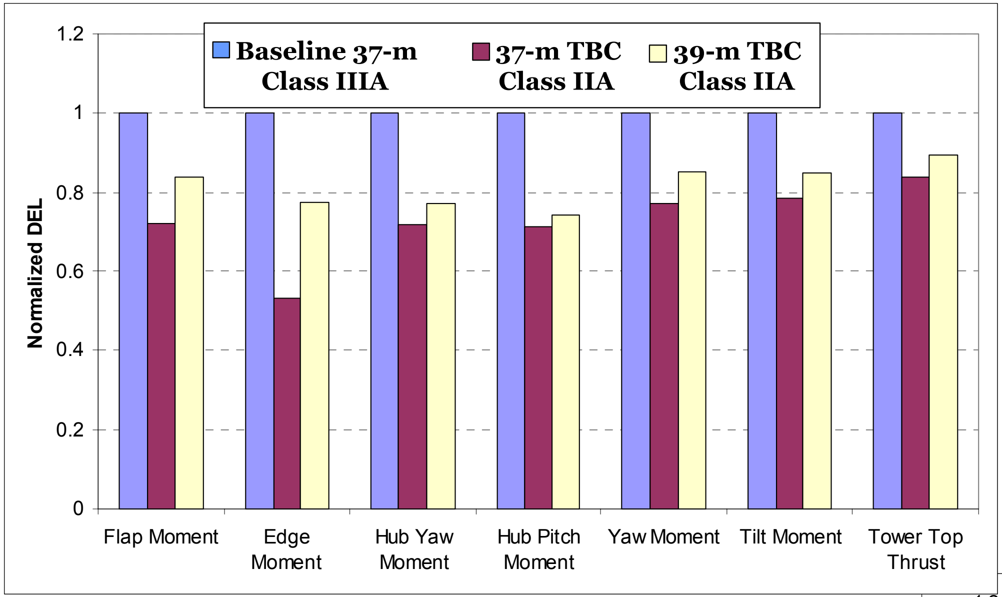
Influence of Coupling on COE



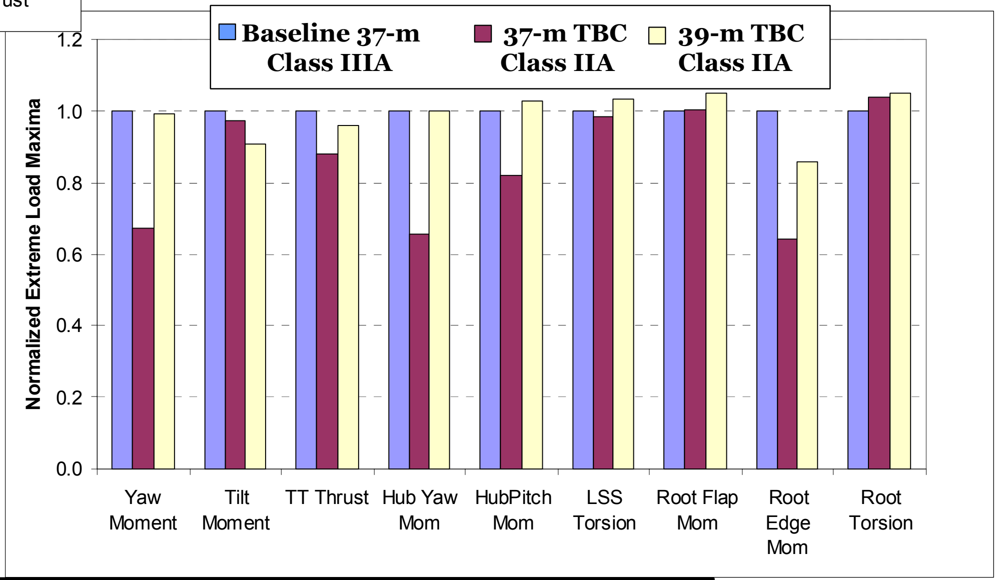
Influence of Carbon on COE
No Coupling



Influence of Coupling on Loads
Pitch-Regulated Design Example

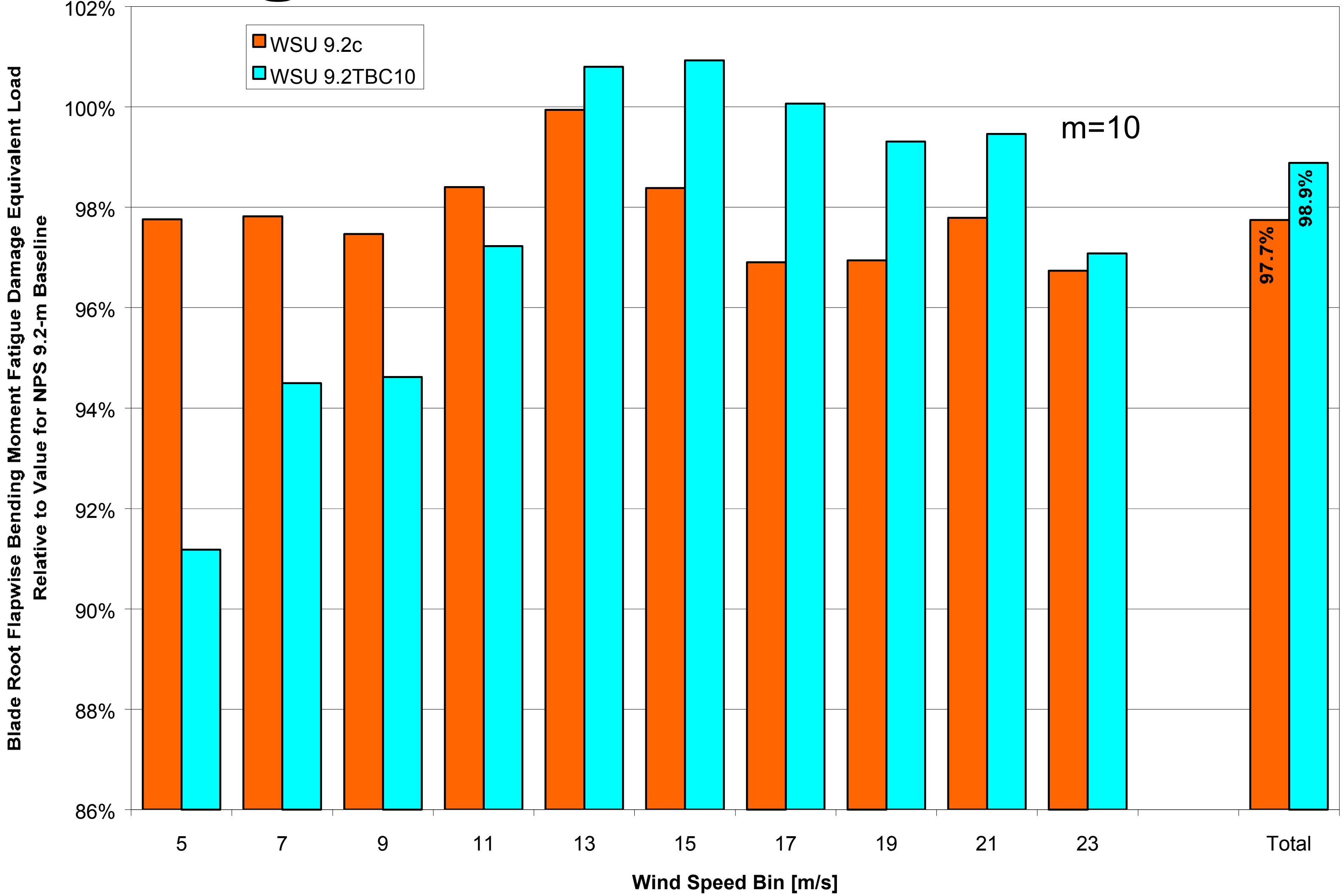


Key DELs Kept Below Class3A Baseline Values, Even at Class 2 Mean Wind Speeds and Larger Dia.



Demonstrated Potential to Reduce or Maintain Key Extreme Loads Close to Baseline Values

9.2-m Blade Flapwise Fatigue Stall-Regulated Turbine (Sandia LIST)



WS9.2c is an Uncoupled Carbon/Glass Hybrid Blade
WSU9.2TBC10 is a Twist-Flap Coupled Carbon/Glass Hybrid Blade
NPS9.2 is the Baseline, Uncoupled All-Glass Blade

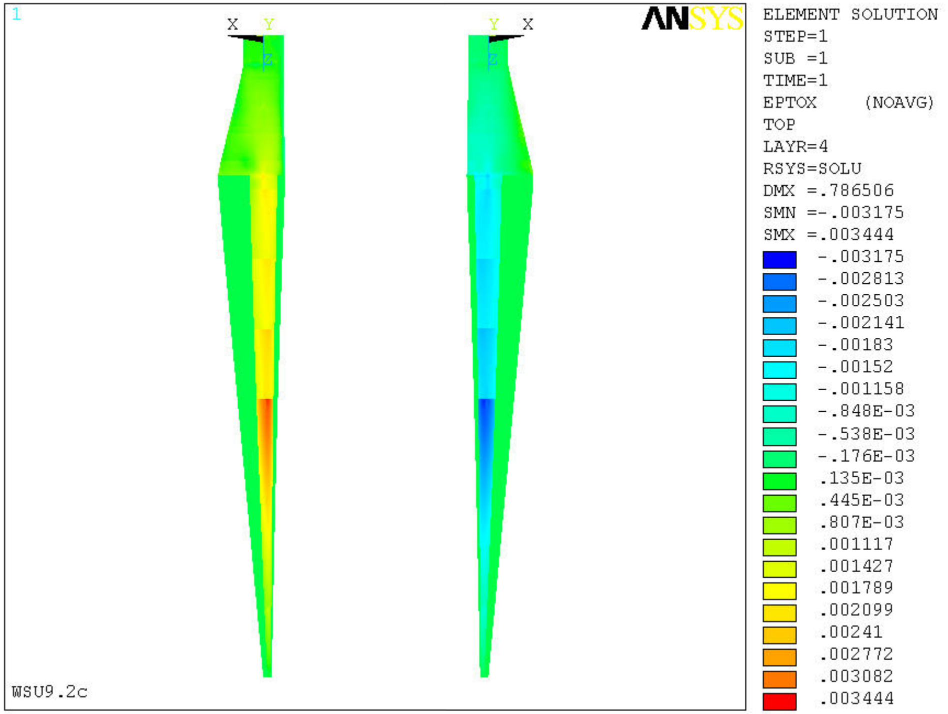
Peak Carbon Fiber Strain, 9.2-m Blades

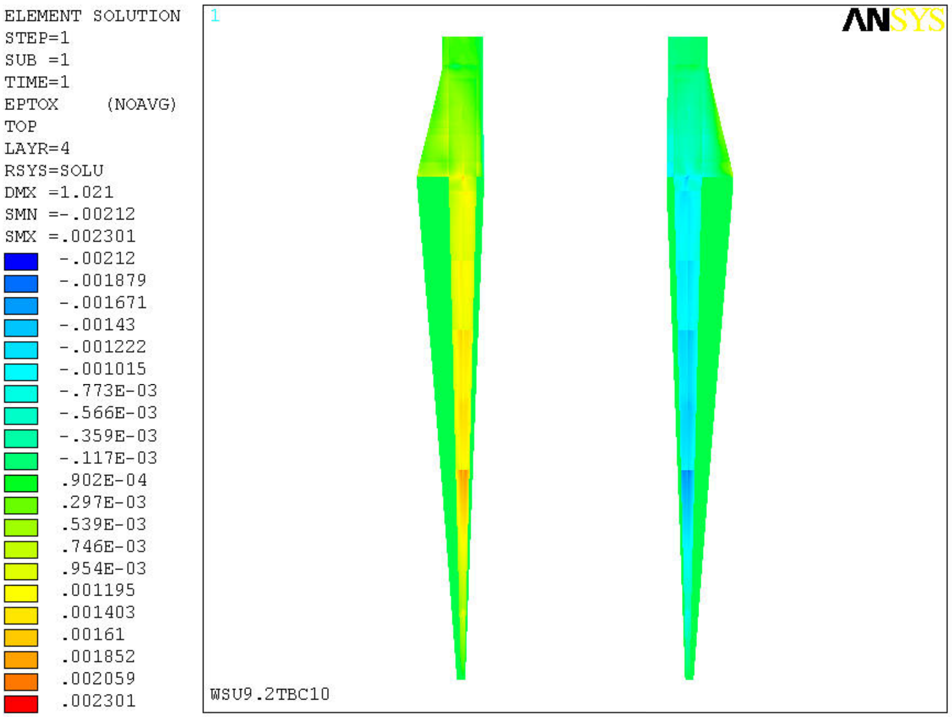
Uncoupled Blade

Max 3444 μstrain

2% Margin on Static Axial Strain

8% Margin on Axial Strain Fatigue





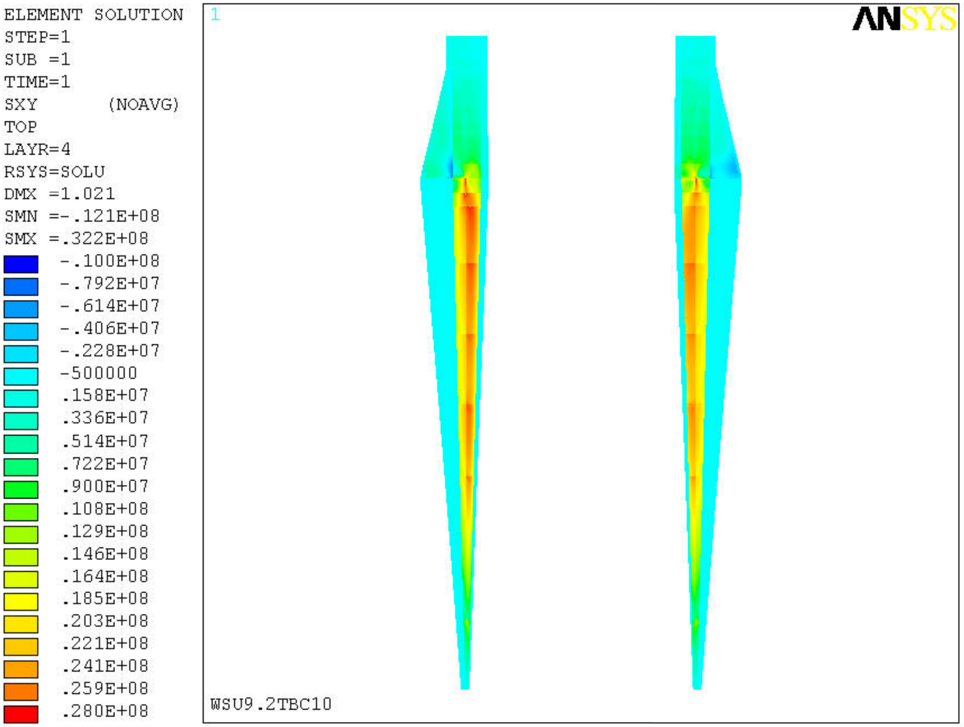
Coupled Blade

Max 2301 μstrain

52% Margin on Static Axial Strain

65% Margin on Axial Strain Fatigue

Shear Stress, 9.2-m Coupled Blade

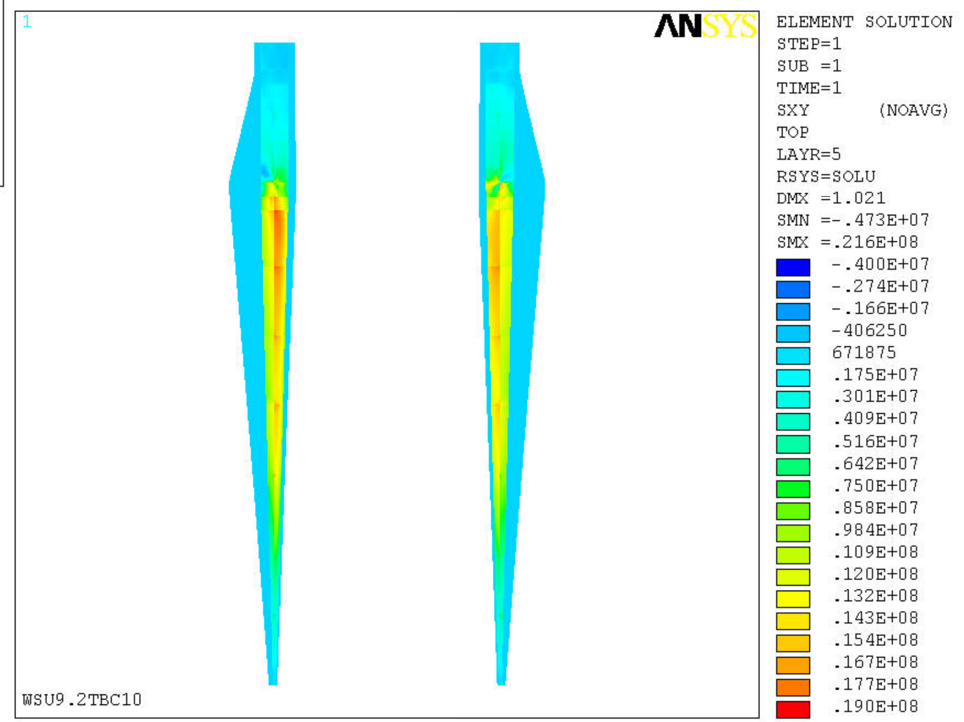


20° Carbon Fibers

32.2 MPa Peak Shear Stress

8% Margin on Static Shear Strength

Shear Fatigue Allowable is Unknown



0° Glass Fibers

21.6 MPa Peak Shear Stress

-7% Margin on Static Shear Strength

Shear Fatigue Allowable is Unknown

Twist-Flap Coupled Blade Studies Conclusions to Date

- Cost of energy benefits seem to improve with increasing coupling – no interim sweet spot has been found
- Shear strength and fatigue issues will probably be the key design challenge
- Coupling in the spar caps and skins is preferable to confining it to either region
- Coupling in the spar caps only is preferable to coupling in the skins only
- Must maintain some ±45° material in the skins
- Benefits of coupling for stall-regulated turbines is questionable